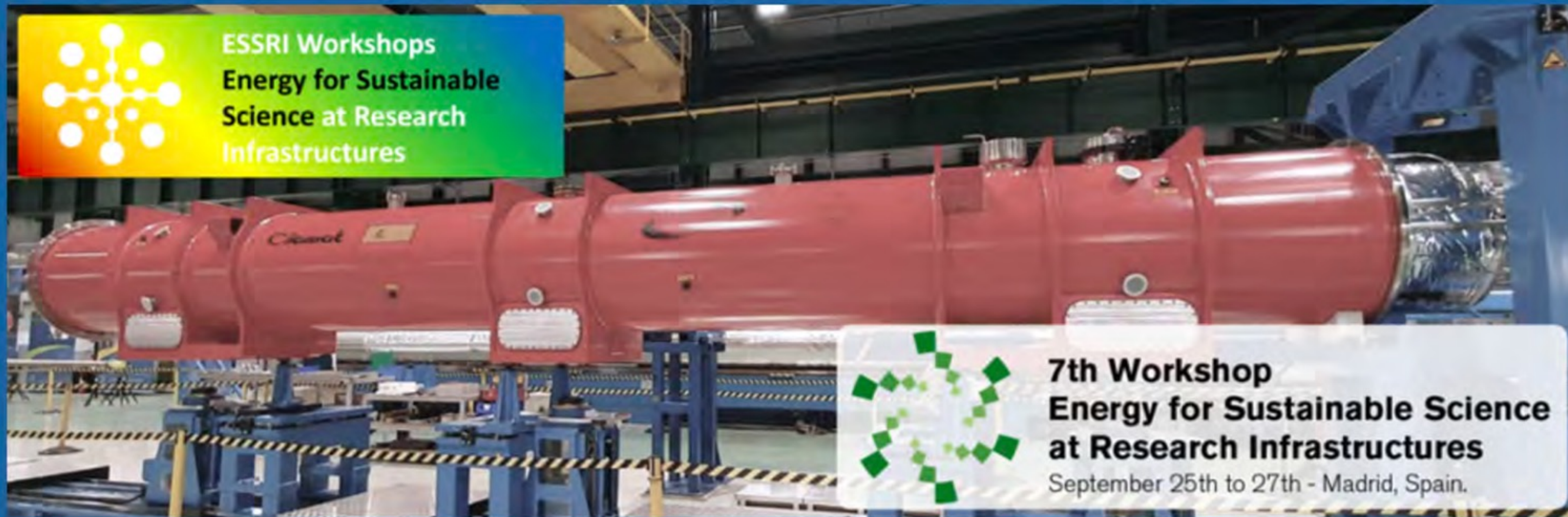


ESSRI, Energy for Sustainable Science at Research Infrastructures

25–27 Sept 2024
Europe/Madrid timezone

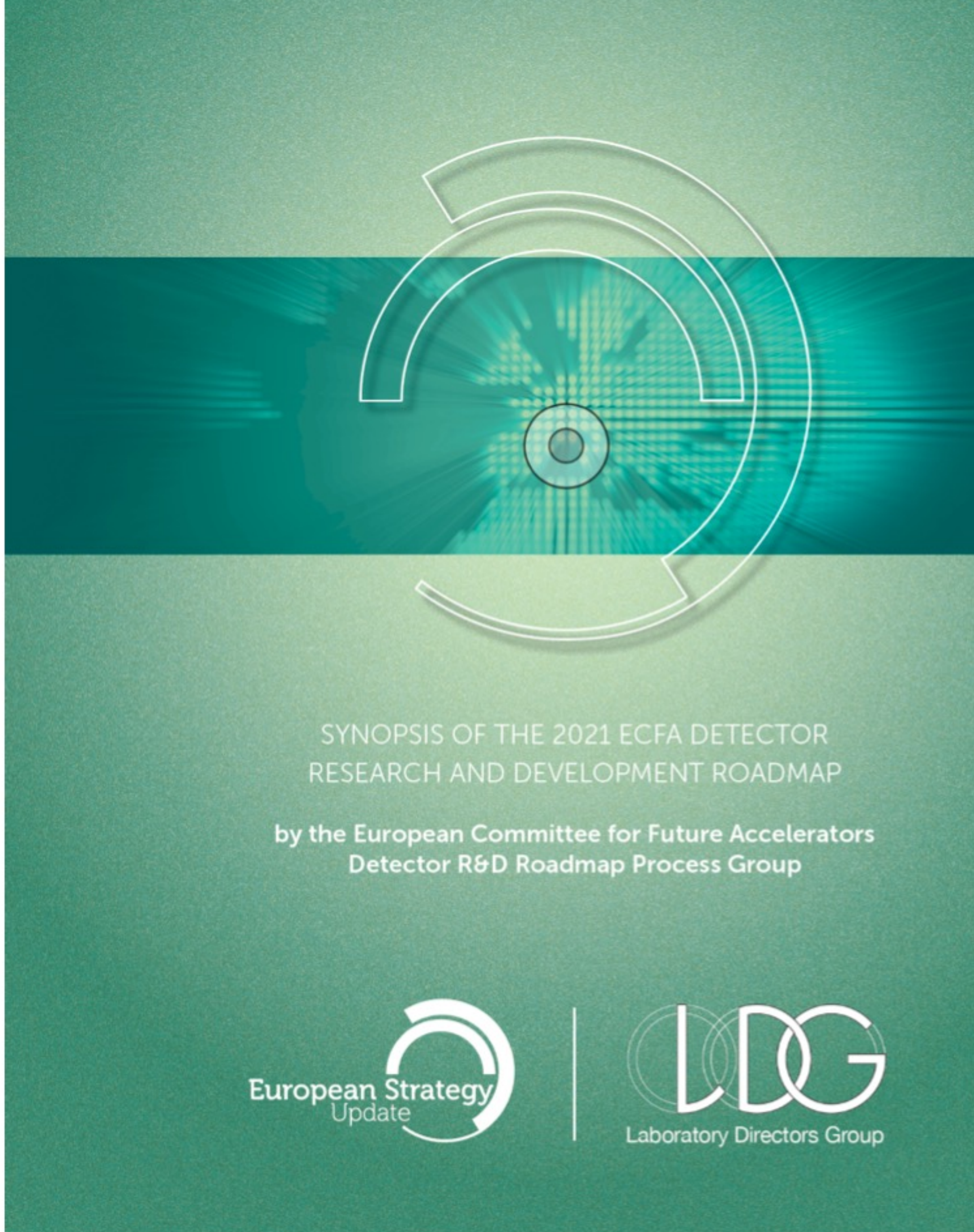
General Life Cycle Analysis in EU Colliders
LDG Working Group on
"Sustainability Assessment of future Accelerators"

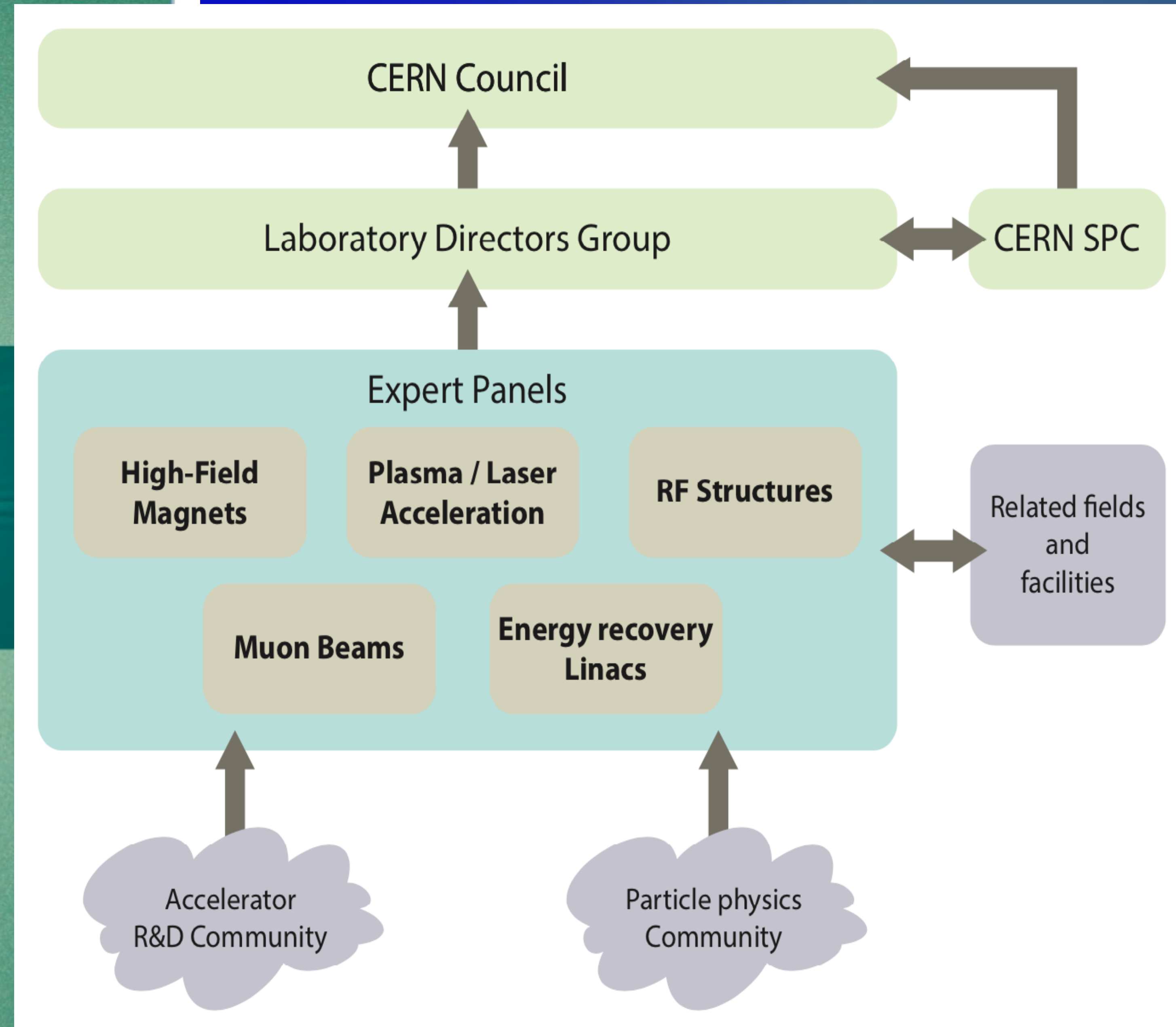
C.Bloise (INFN-LNF), M.Titov (CEA-Saclay)
on behalf of the LDG WG

Madrid 26 September 2024

https://cds.cern.ch/record/2800190/files/146-138-PB.pdf

LDG: CERN Advisory Committee to supervise development of the roadmap for the accelerator R&D





Sustainability Working Group (added to 5 LDG Expert Panels) in January 2024

WG Mandate and Composition

Development of Guidelines and a minimum set of Key Indicators for the sustainability assessment of future accelerators

Panel consisting of 14 members with technical expertise in evaluation of accelerator sustainability and future collider project representatives

Ensuring broad community representation:

- Sustainability Lab. Panels established at CERN, DESY, ESS, NIKHEF, STFC
- ICFA Sustainability Panel
- EU- Horizon Programs
- Future accelerator projects: FCC, ILC, CePC, CLIC/Muon, LHeC, C3

- Invited experts on specific topics

Walib Kaabi	iSAS, PERLE
Roberto Losito	CERN sust. panel
Ben Shepherd	STFC sust. Task Force
Andrea Klumpp	DESY sust. panel
Hannah Wakeling	ISIS-II Neutron & Muon Source
Patrick Koppenburg	NIKHEF sust. panel
Johannes Gutleber	FCC
Yuhui Li	CePC
Benno List	ILC
Emilio Nanni	ICFA and CCC
Vladimir Shiltsev	LHeC, FCC-eh
Steinar Stapnes	CLIC, Muon collider
Caterina Bloise	Co-Chair
Maxim Titov	Co-Chair, EU-EAJADE

in the Editorial Board also

Enrico Cennini	CERN Procurement Service
Beatrice Mandelli	CERN DT group
Thomas Schoerner	ILC sustainability studies WG

Working Group Activity

Broad range of topics shared

- Reports from CERN and STFC sustainability panels, ESS, Snowmass ITF
- Evaluations carried out for future Higgs factories, FCC, ILC, C3 and CePC
- On key LCA issues
- Invited contributions on Decarbonisation for Large RI, H.Pantelidou (ARUP), on LCA of engineering civil works for the FCC, D. Mauree (WSP), Eu-Horizon Project RF2.0, G. DeCarne (KIT), Reduction of GHGs in particle detectors, B. Mandelli (CERN)

WG Report is being elaborated

1st LDG WG Meeting on the Sustainability Assessment of Accelerators

Tuesday 19 Mar 2024, 15:00 → 17:00 Europe/Zurich

Caterina Bloise (Laboratori Nazionali di Frascati (LNF)), Maksym Titov (IRFU, CEA Saclay, Université Paris-Saclay (FR))

Description htt…

- 15:00 → 15:30 Presen…
- 15:30 → 16:00 Self-in…
- 16:00 → 16:15 Calend…
- 16:15 → 16:30 Agend…

2nd LDG WG Meeting on the Sustainability Assessment of Accelerators

Monday 8 Apr 2024, 15:00 → 17:00 Europe/Zurich

Description https://cern.zoom.us/s/66928561166?pwd=OWRyNVpOVDFLQ0kwZVBCYTFMa0NkZz09#success

- 15:00 → 15:15 News, Minutes Approval (1st Meeting), Calendar for the next WG Meetings
  Speakers: Caterina Bloise (Laboratori Nazionali di Frascati (LNF)), Dr Maksym Titov (IRFU, CEA Saclay, Université Paris-Saclay (FR))
  LDG_WG_Sustaina…
- 15:15 → 15:30 CERN Sustainability Panel & Framework for estimating the evolution of CO2 load from Energy in France.
  Speaker: Roberto Losito (CERN)
  Sustainability in fut… Sustainability in fut…
- 15:40 → 15:55 Sustainable Accelerator R&D in the UK: Key Inputs to the LDG WG Activities
  Speakers: Ben Shepherd, Mr Ben Shepherd
  2024-04-08 Shephe…

3rd LDG WG Meeting on the Sustainability Assessment of Accelerators

Monday 29 Apr 2024, 15:00 → 17:15 Europe/Zurich

Description https://cern.zoom.us/j/61888272480?pwd=S2ZpRWlaS2xoTFBsQmxaZDR5T25xZz09

- 15:00 → 15:05 News and Minutes Approval
  Speakers: Caterina Bloise (Laboratori Nazionali di Frascati (LNF)), Dr Maksym Titov (IRFU, CEA Saclay, Université Paris-Saclay (FR))
  2024_04_3rd-SUST… 2024_04_3rd-SUST… LDGSAW_M1_Minu… LDGSAW_M2_Minu…
- 15:10 → 15:30 Sustainability Studies for ILC/CLIC: Key Inputs to the LDG WG Report
  Speaker: Dr Benno List (Deutsches Elektronen-Synchrotron (DE))
  LC_Sustainability_L… LC_Sustainability_L…
- 15:40 → 16:00 Sustainability Studies for FCC: Key Inputs to the LDG WG Report¶
  Speaker: Johannes Gutleber (CERN)
  FCC-2404041500-J… FCC-2404041500-J…
- 16:10 → 16:30 Sustainability Studies for C3: Key Inputs to the LDG WG Report¶
  Speakers: Emilio Nanni (SLAC National Accelerator Laboratory), Emilio Nanni
  LDG_C3_Sustainabi…
- 16:40 → 17:00 Sustainability Studies for CEPC: Key Inputs to the LDG WG Report¶
  Speaker: yuhui li (Institute of High Energy Physics)

6th LDG WG Meeting on the Sustainability Assessment of Accelerators

Monday 24 Jun 2024, 15:00 → 17:00 Europe/Zurich

Description https://cern.zoom.us/j/61888272480?pwd=S2ZpRWlaS2xoTFBsQm…

- 15:00 → 15:15 News and Minutes Approval
  Speakers: Caterina Bloise (INFN e Laboratori Nazionali di Frascati (IT)), Dr Maksym…
  LDGSAW_M5_Minu…
- 15:15 → 15:35 Energy Efficiency of Future Colliders: Snowmass Implementation T… Discussions ¶
  Speaker: Vladimir Shiltsev
- 15:35 → 15:55 Strategies to reduce the use of GHGs in particle detectors
  Speaker: Beatrice Mandelli (CERN)
- 15:55 → 16:10 A Summary about HEP sustainability workshop
  Speaker: Dr Hannah Wakeling (John Adams Institute, Oxford University)
- 16:15 → 16:45 Discussion & Next Steps for the LDG WG Report
  Speaker: All

5th LDG WG Meeting on the Sustainability Assessment …

Monday 3 Jun 2024, 15:00 → 17:00 Europe/Zurich

Description https://cern.zoom.us/j/61888272480?pwd=S2ZpRWlaS2xoTFBsQmxaZDR5T25xZz09

- 15:00 → 15:10 News and Minutes Approval
  Speakers: Caterina Bloise (Laboratori Nazionali di Frascati (LNF)), Dr Maksym Titov (IRFU, CEA Saclay, Université Pari…
  LDG_SAW_5_DocT… LDG_SAW_5_DocT… LDGSAW_M3_Minu… LDGSAW_M4_Mi…
- 15:10 → 15:30 RF2.0 Horizon Europe project
  Speaker: Giovanni De Carne (Karlsruhe Institute of Technology)
  GiovanniDeCarne_… GiovanniDeCarne_I…
- 15:40 → 16:10 Initial Discussion about Structure & Next Steps for the LDG WG Report
  Speaker: All
  DocTopics LC_Sustainability_L…
- 16:10 → 16:40 Report from Sustainability WG at the Open LDG Meeting @BNL (June 6-7): Discussion
  Speakers: Caterina Bloise (Laboratori Nazionali di Frascati (LNF)), Maxim TITOV (CEA Saclay)
  1_2024_06_BNL-U…

4th LDG WG Meeting on the Sustainability Assessment of Accelerators

Monday 13 May 2024, 15:00 → 17:00 Europe/Zurich

Description https://cern.zoom.us/j/61888272480?pwd=S2ZpRWlaS2xoTFBsQmxaZDR5T25xZz09

- 15:00 → 15:05 News and Minutes Approval
  Speakers: Caterina Bloise (Laboratori Nazionali di Frascati (LNF)), Dr Maksym Titov (IRFU, CEA Saclay, Université Paris-Saclay (FR))
  2024_05_4th-SUST… 2024_05_4th-SUST…
- 15:10 → 15:30 ARUP experience on decarbonisation and large research infrastructure
  Speaker: Heleni Pantelidou (ARUP)
- 15:40 → 16:00 Key LCA Issues
  Speaker: Dr Hannah Wakeling (John Adams Institute, Oxford University)
  2024_05_13_LDG_…
- 16:00 → 16:15 General LCA Discussion
- 16:15 → 16:55 Towards Open LDG Meeting @BNL (June 6-7): Sustainability Discussion
  Speakers: Caterina Bloise (Laboratori Nazionali di Frascati (LNF)), Maxim TITOV (CEA Saclay)
- 16:55 → 17:00 AoB

Working Group Report

Structure and basic content suggested by reports to the WG and follow-up discussions

Draft report is expected by end of 2024

Report as an input document to the ESPPU due by March 2025

An homogeneous evaluations of all issues will probably need more time to develop and deserves a strategy to be pursued

Work Progress Status

- Editorial work assigned, Report elaboration advanced, most of the topics drafted
- Content:
  - Presentation of relevant topics
  - Comments and questions to be addressed
  - Some proposals for recommendations to be discussed
  - Focus is on sustainability assessment of projects for future colliders

7th LDG WG Meeting on the Sustainability Assessment of Accelerators

Monday 15 Jul 2024, 15:00 → 17:00 Europe/Zurich

Description https://cern.zoom.us/j/61888272480?pwd=S2ZpRWlaS2xoTFBsQmxaZDR5T25xZz09

15:00 → 15:15 **News and Minutes Approval**
Speakers: Caterina Bloise (INFN e Laboratori Nazionali di Frascati (IT)), Dr Maksym Titov (IRFU, CEA Saclay, Université Paris-Saclay (FR))
LDGSAW_M6_Minu...

15:15 → 16:45 **Next Steps for the WG report: Discussion on Content and Chapter Editors**
Speakers: Caterina Bloise (Laboratori Nazionali di Frascati (LNF)), Dr Maksym Titov (IRFU, CEA Saclay, Université Paris-Saclay (FR))
15072024_Discuss...

8th LDG WG Meeting on the Sustainability Assessment of Accelerators

Monday 26 Aug 2024, 15:00 → 17:00 Europe/Zurich

Description https://cern.zoom.us/j/61888272480?pwd=S2ZpRWlaS2xoTFBsQmxaZDR5T25xZz09

15:00 → 15:15 **News and Minutes Approval**
Speakers: Caterina Bloise (INFN e Laboratori Nazionali di Frascati (IT)), Dr Maksym Titov (IRFU, CEA Saclay, Université Paris-Saclay (FR))

15:15 → 15:45 **FCC LCA study: sensitivity of the use of databases and EPDs to the final result.**
Speakers: Dasardan Mauree (WSP / BG Ingénieurs Conseils SA), Johannes Gutleber (CERN)

15:45 → 16:45 **Current Status of the WG report: Discussion on Content**
Speakers: Caterina Bloise (Laboratori Nazionali di Frascati (LNF)), Dr Maksym Titov (IRFU, CEA Saclay, Université Paris-Saclay (FR))
26082024_EDITOR... 26082024_EDITOR...

16:45 → 16:55 **AoB**

9th LDG WG Meeting on the Sustainability Assessment of Accelerators

Monday 16 Sept 2024, 15:00 → 17:00 Europe/Zurich

Description https://cern.zoom.us/j/61888272480?pwd=S2ZpRWlaS2xoTFBsQmxaZDR5T25xZz09

15:00 → 15:15 **News and Minutes Approval**
Speakers: Caterina Bloise (INFN e Laboratori Nazionali di Frascati (IT)), Dr Maksym Titov (IRFU, CEA Saclay, Université Paris-Saclay (FR))
LDGSAW_M7_Minu... LDGSAW_M8_Minu...

15:15 → 15:45 **Introduction to Current Status of the WG report:**
Speakers: Caterina Bloise (Laboratori Nazionali di Frascati (LNF)), Dr Maksym Titov (IRFU, CEA Saclay, Université Paris-Saclay (FR))
160924_1.pptx

15:45 → 16:45 **Discussion on Content**
Speaker: All

16:45 → 16:55 **AoB**

Report : Social-Economic Benefit Analysis

Social - Economical Benefits of HEP Research Infrastructures in Relation to the UN Sustainability Development Goals (environment, economy, society)

- SDG Reference Matrix from UN (2024)
  - Accelerator and Detector R&D (strategic ECFA R&D Roadmap)
  - Economic growth (regional, international, developing countries)
  - Education, Innovation, International Cooperation, Cultural Exchange

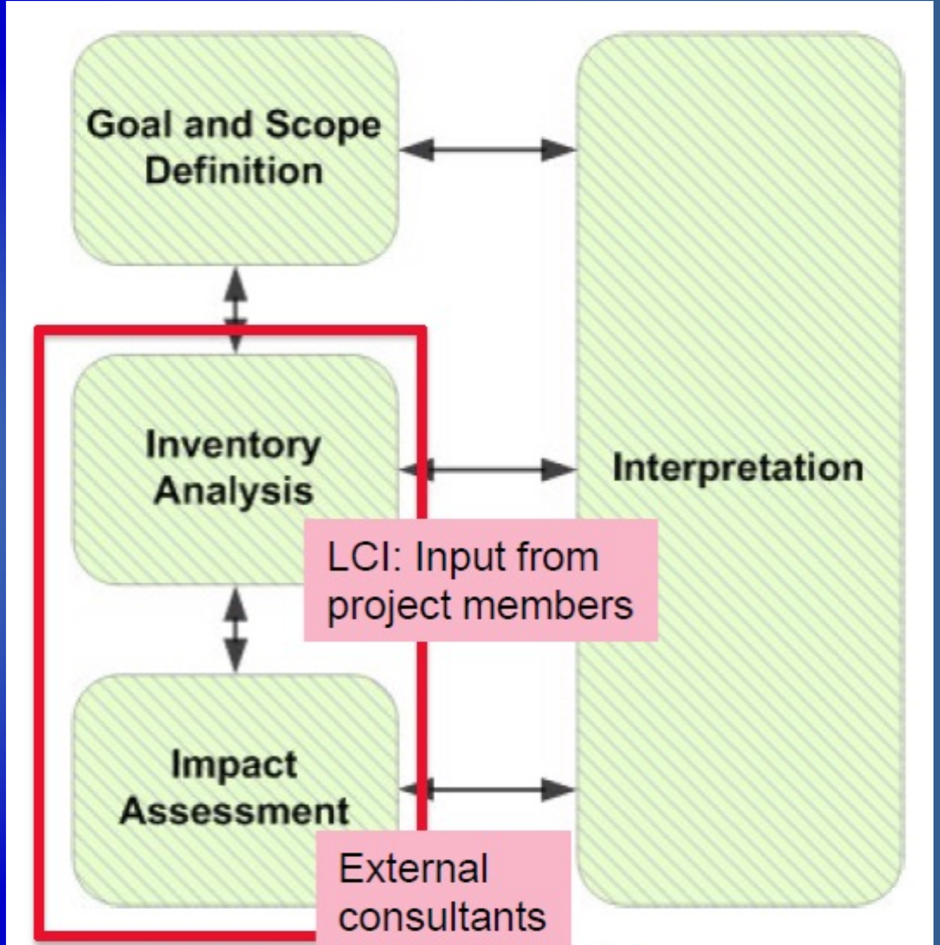
Reference for the integrated model FCC

- Comprehensive sustainability assessment based on Cost-Benefit Analysis:
  - Guidelines on cost estimation of RI from ESFRI (2019)
  - EU Policies
    - Global Reporting Initiative
    - European Sustainability Reporting Standards
    - European Union Eco-Management and Audit Scheme (EMAS)
    - EC Economic Appraisal Vademecum 2021-2027
    - National Guidelines (France, Germany, Switzerland, …)
  - Carbon Footprint Accounting and Reporting
    - Shadow Carbon Cost

Report : Life-Cycle Assessment

Life-Cycle Assessment for Future Accelerators – Methodology and Reporting:

- Goal and Scopes
- Methodology
  - Impact Categories
    - Midpoint and Endpoint Categories
  - Impact of Emission on Climate Change, GWP_{100}
  - Beyond GWP : ReCiPe2016, ILCD2011, CML-IA2012
- Life Cycle Inventory
  - Construction Phase
  - Operation Phase
  - Decommissioning Phase
- Assessment
- Interpretation
- Evaluation of Uncertainties
- Environmental Product Declaration



LCA Framework according to ISO 10040
Public Domain, https://commons.wikimedia.org/w/index.php?curid=40862556

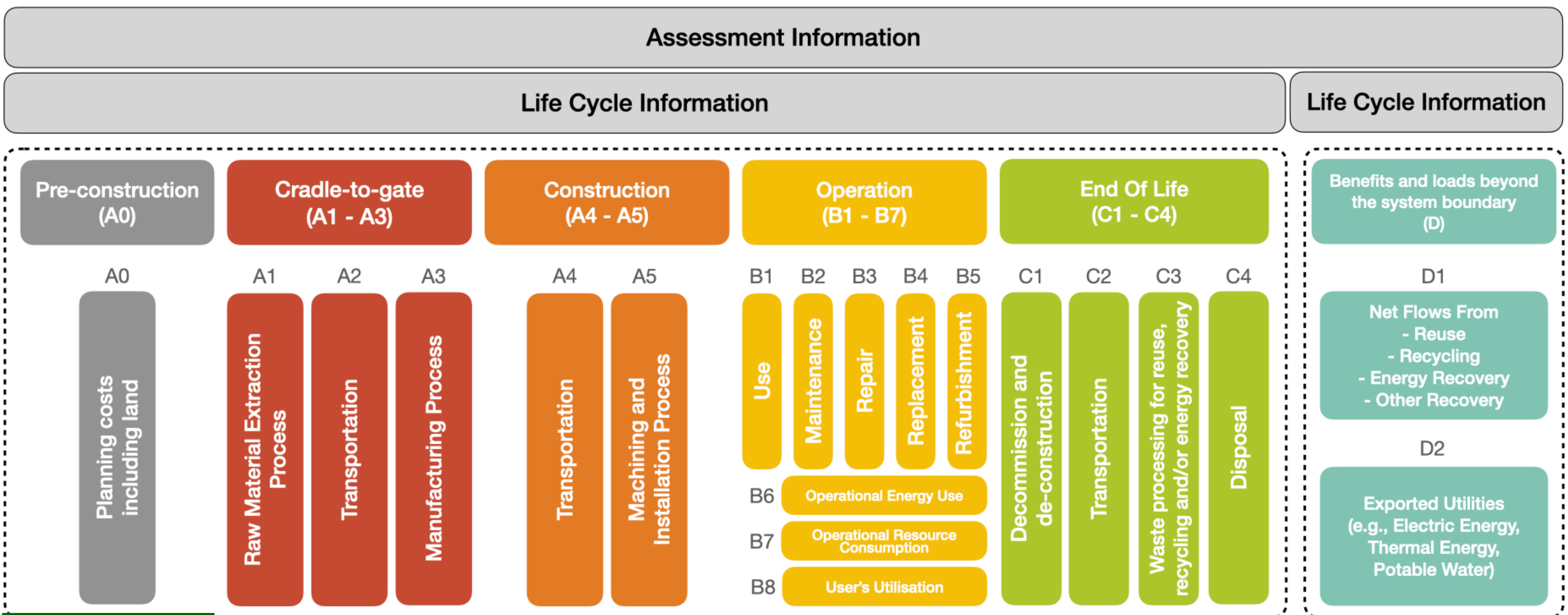
B. List
H. Wakeling

Life-Cycle Assessment (LCA) : Goal and Scope

Product, System, Process to be evaluated within declared boundaries

Goal and Scope depend on the phase of the accelerator project and to the target : Researchers, Management, Authorities, Public

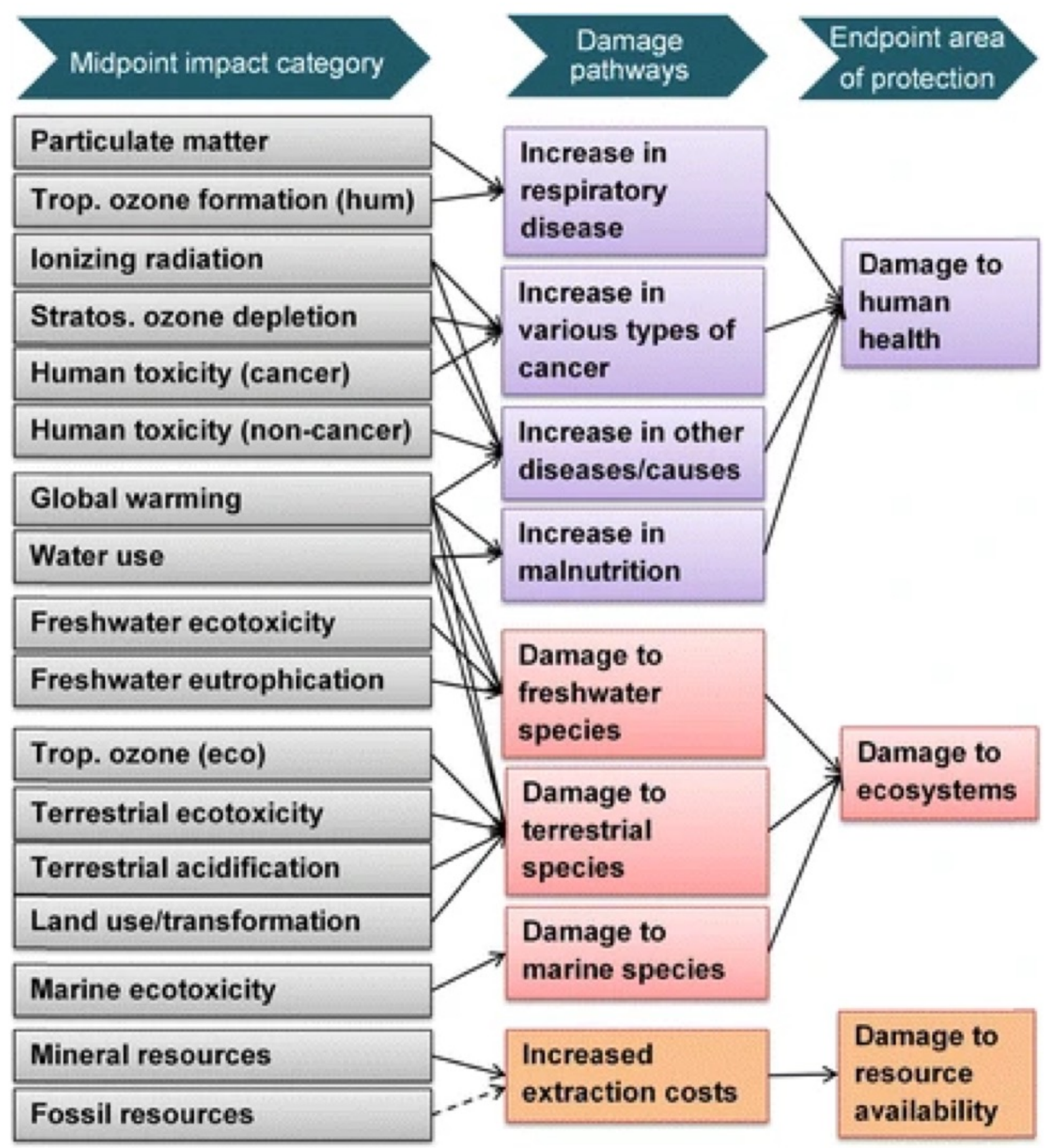
- functional units: accelerator, supporting infrastructures, cryogenic systems, detector, computing
- Boundaries: Cradle-to-gate, Cradle-to-grave
- Methodology: Impact Categories Analyzed



H. Wakeling

BS EN 17472:2022

LCA categories



ReCiPe2016

Conversion factors used in the evaluation of Midpoint categories are usually considered reliable

Endpoint evaluations are obtained by weighting results obtained on Midpoint ones

A number of categories classes exist

European Production Declarations from the International Reference Life Cycle Data system (ILCD) follow EN 15804

Report : GHG Emissions

- Green House Gas Emissions footprint for future accelerator facilities:

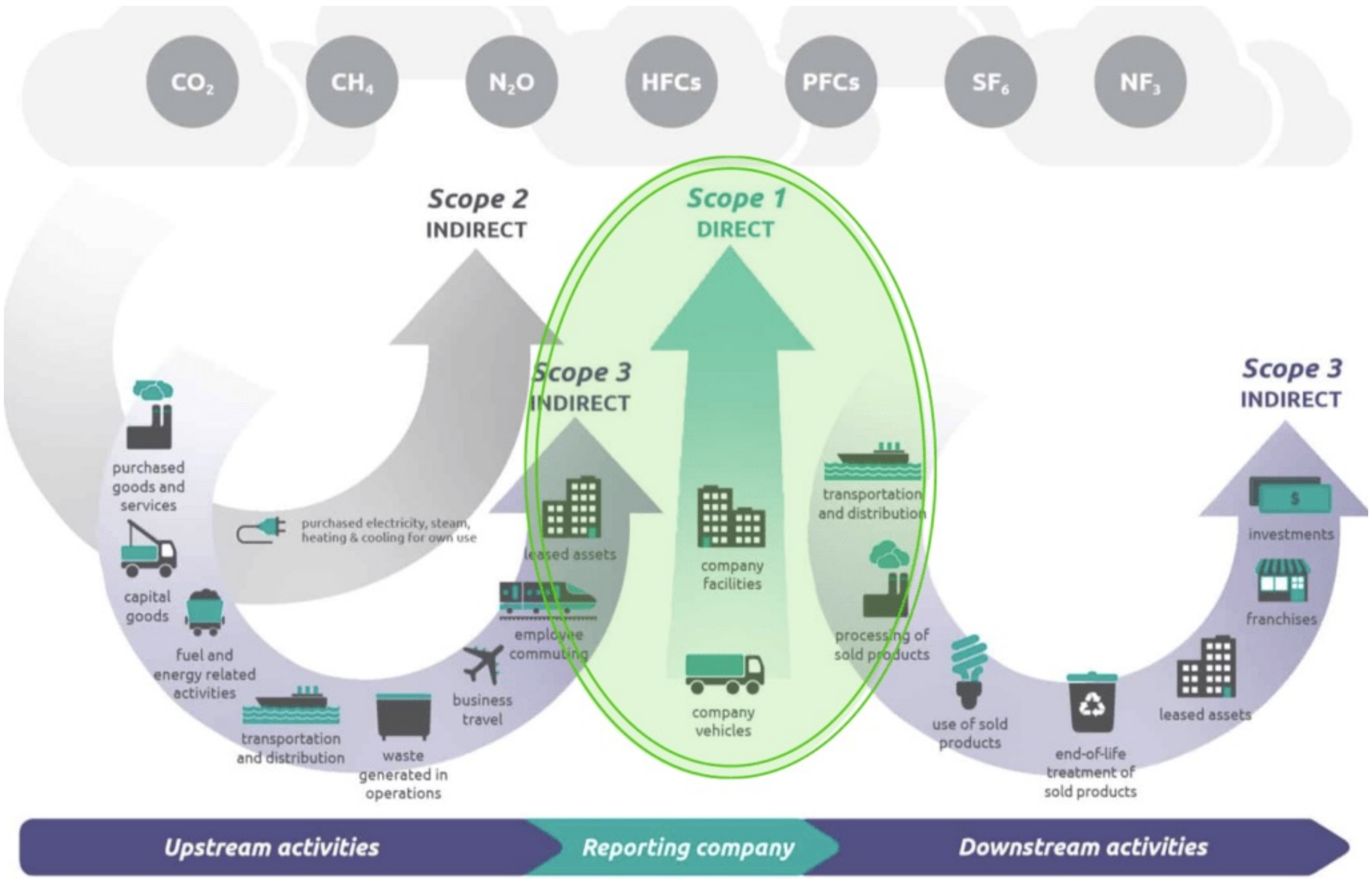
Developing a tool and guidance for quantification could be a good recommendation for the strategy: e.g. evaluate and optimise CO_2 impact in a staged approach at early concept phase, CDR and TDR levels over the full lifecycle

- Civil engineering works LCA studies for accelerator infrastructure (e.g. tunnels, caverns) and Civil engineering (LCA A1-A5)
  - Excavated Material
- Accelerator construction: early assessment of areas with the largest emission, beam line shielding, steel girders and supporting structures, magnets, RF cavities, power supplies, material manufacturing
- Accelerator operation: power for: air conditioning and water cooling, cryogenic plants, RF and klystrons, Magnets
- Operation of Particle detectors and computing:
  - Impact of gases for particle detectors
- Decommissioning:
  - Radioactive waste
  - Recycling
  - Reuse

Green House Gases Emissions

According to the 2015 Paris Agreement carbon emissions have to be halved by 2030.

LCA Boundaries for reporting on GHG emissions are often categorised into Scope 1, 2, 3



https://ecochain.com/blog/scope-1-emissions-explained/

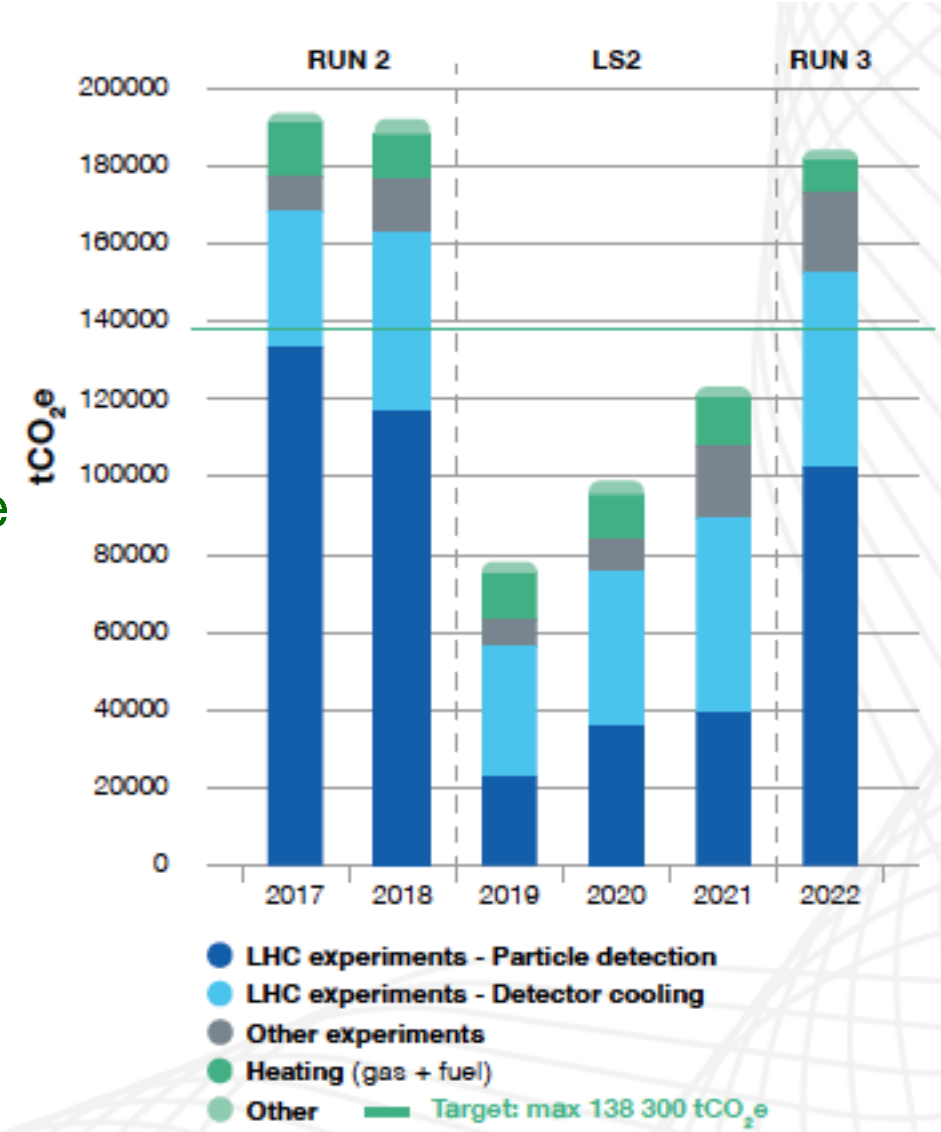
Decarbonisation and Large HEP RI

CERN publishes environmental reports following standards of Global Reporting Initiative since 2017

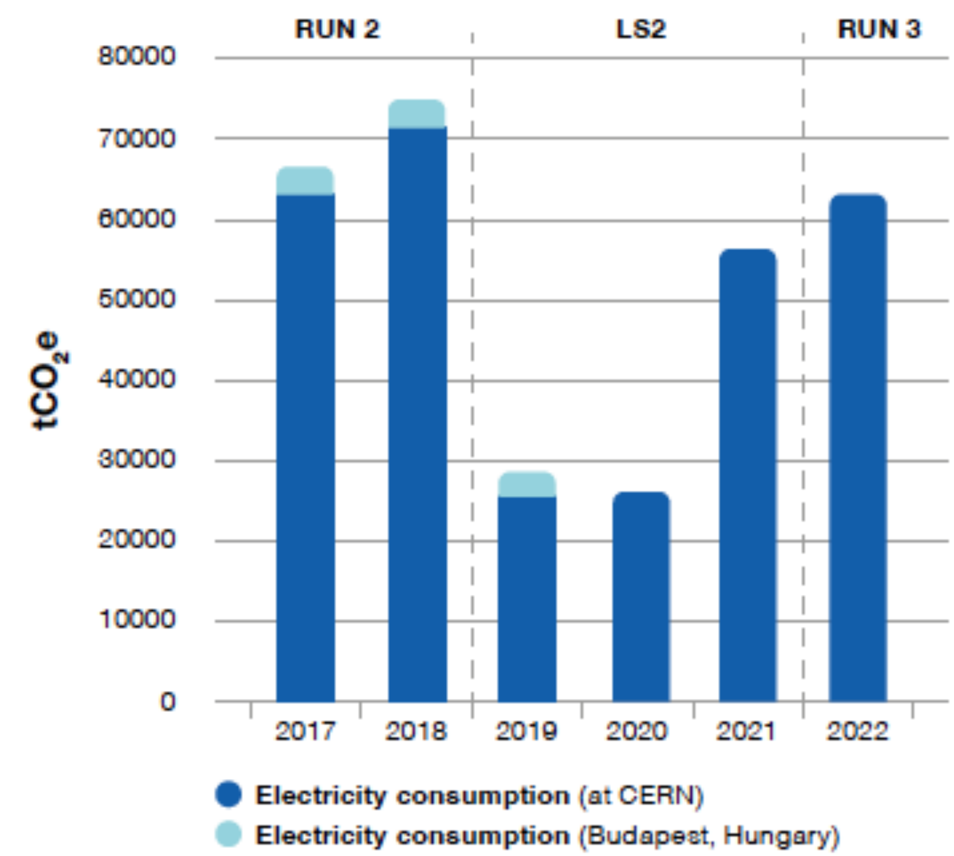
CERN has developed a strategy for energy sourcing and monitoring obtaining the ISO50001 certification for energy management

Scope 1 Direct Emissions: @LHC are dominated by gas mixtures used by particle detectors and detector cooling

Scope 2 Emissions (Energy Consumption): location-based methodology provides emission factors depending on energy sources in use



CERN SCOPE 1 EMISSIONS FOR 2017–2022 BY CATEGORY
"Other" includes air conditioning, electrical insulation, emergency generators and the fuel consumption of the CERN vehicle fleet.



CERN SCOPE 2 EMISSIONS FOR 2017–2022
Emission calculations for electricity follow a location-based methodology, with average yearly emission factors taken from ADEME Base Empreinte©. From 2017 to 2019, CERN operated a data centre at the Wigner Centre in Budapest, Hungary, for which the emissions are also shown. The location-based emission factors used for Hungary were taken from Bilan Carbone® V8.4.

Reference: CERN Environment Report 2021-22

Report : Mitigation and Compensation Strategies

Mitigation and Compensation Strategies, Decarbonisation and Impact Reduction

- Optimization of large civil & accelerator construction footprint & better/greener materials (inventory of concrete, steel, Cu, niobium)
- Responsible procurement
- Energy/power optimization (improving energy efficiency of key technologies) and recuperation (heat management, ERL, …)
- Heat Recovery and supply
- Investment in R&D on green technologies
- Nature-based interventions for carbon removal (e.g. environmental studies, integration in local environment)

Annexes:

Snowmass process and P5 Report
Plans to reduce accelerator energy consumption in China
Obligations, Legislation

Summary and Outlook

- The *WG mandate* is to develop a motivated list of key parameters for the sustainability assessment of future accelerators
  → *inputs* from different *sustainability initiatives* and panels

- *Sustainability assessment for future large-scale accelerator infrastructures is quite complex*

  → assessment criteria needs to be properly tuned to the maturity of the project
  → differently developed for Researchers, Management and Society

- Editorial group has advanced in writing the Report aiming to *elaborate a proposal* for the LDG on time to be submitted as an *input to the ESPPU in March 2025*

Europe-Horizon Sustainability - Supporting Programs

- ✓ *Innovation Fostering in Accelerator Science and Technology (I.FAST): https://ifast-project.eu*
- ✓ *Europe-America-Japan Accelerator Development Exchange Programme (EAJADE): https://www.eajade.eu/*
- ✓ *Innovate for Sustainable Accelerating Systems (iSAS): https://indico.ijclab.in2p3.fr/event/9521/*

https://indico.cern.ch/event/1326603/timetable/#20240215.detailed

WP11 Overview

task 1: Sustainable Concepts for RIs: networking, workshops on selected topics
deliverable: report
1) System Efficiency of Accelerator Concepts (N.Catalan Lasheras, CERN)
2) Key Technologies and Components for High Efficiency (A.Sunesson [C.Martins], ESS)
3) Cross Linking Accelerator R&D with Industrial Approaches (P.Spiller, GSI)
4) Ecological Concepts (D. Voelker, DESY)

task 2: High Efficiency Klystron (O.Brunner CERN, THALES, ULANC)
- deliverable: industrial prototype
- replacing klystrons in LHC

task 3: Permanent Combined Function Magnets for Light Sources (B.Shepherd, UKRI, DLS, KYMA, DESY)
- deliverable: magnet prototype, applicable for Diamond upgrade
- several advantages of permanent magnets, not just power consumption

iSAS Objectives – *Technology Areas*

- **TA#1: energy-savings from RF power** – *While great strides are being made in the energy efficiency of various RF power generators, the objective of iSAS is to ensure additional impactful energy savings through coherent integration of the RF power source with smart digital control systems and with novel tuners that compensate rapidly cavity detuning from mechanical vibrations, resulting in a further reduction of power demands by up to a factor of 3.*
- **TA#2: energy-savings from cryogenics** – *While major progress is being made in reusing the heat produced in cryogenics systems, the objective of iSAS is to develop superconducting cavities that operate with high performance at 4.2 K (i.e., up to 4.5 K depending on the cryogenic overpressure) instead of 2 K, thereby reducing the grid-power to operate the cryogenic system by a factor of 3 and requiring less capital investment to build the cryogenic plant.*
- **TA#3: energy-savings from the beam** – *Significant progress has been achieved in maintaining the brightness of recirculating beams to provide high-intensity collisions to experiments, but most of the particles lose their power through radiation or in the beam dump system. The objective of iSAS is to develop dedicated power couplers for damping the so-called Higher-Order Modes (HOMs) excited by the passage of high-current beams in the superconducting cavities, enabling efficient recovery of the energy of recirculating beams back into the cavities before it is dumped, resulting in energy reduction for operating, high-energy, high-intensity accelerators by a factor ten.*

https://indico.cern.ch/event/1326603/timetable/#20240215.detailed

ESS also participates in iFAST (addition of solar panels to power modulators) and FlexRICAN (studying flexibiility in power supply)

EAJADE Workshop on Sustainability on Future Accelerators (WSFA2023)

MORIOKA, JAPAN, SEPTEMBER 25-27, 2023
Aiina Center, the same venue as LCWS2016, hosted by Iwate University

https://wsfa2023.huhep.org/ ; https://indico.desy.de/event/39980/

Four blocks (not limited to future Higgs Factores and to Linear Colliders):
- ***I. Large-Scale Research Facilities & Sustainability / Life Cycle Assessment(LCA)***
- ***II. Sustainable Accelerator Technologies***
- ***III. Europe-Horizon and National Sustainability-Supporting Programmes***
- ***IV. Green ILC and Local Industries***

https://wsfa2023.huhep.org/

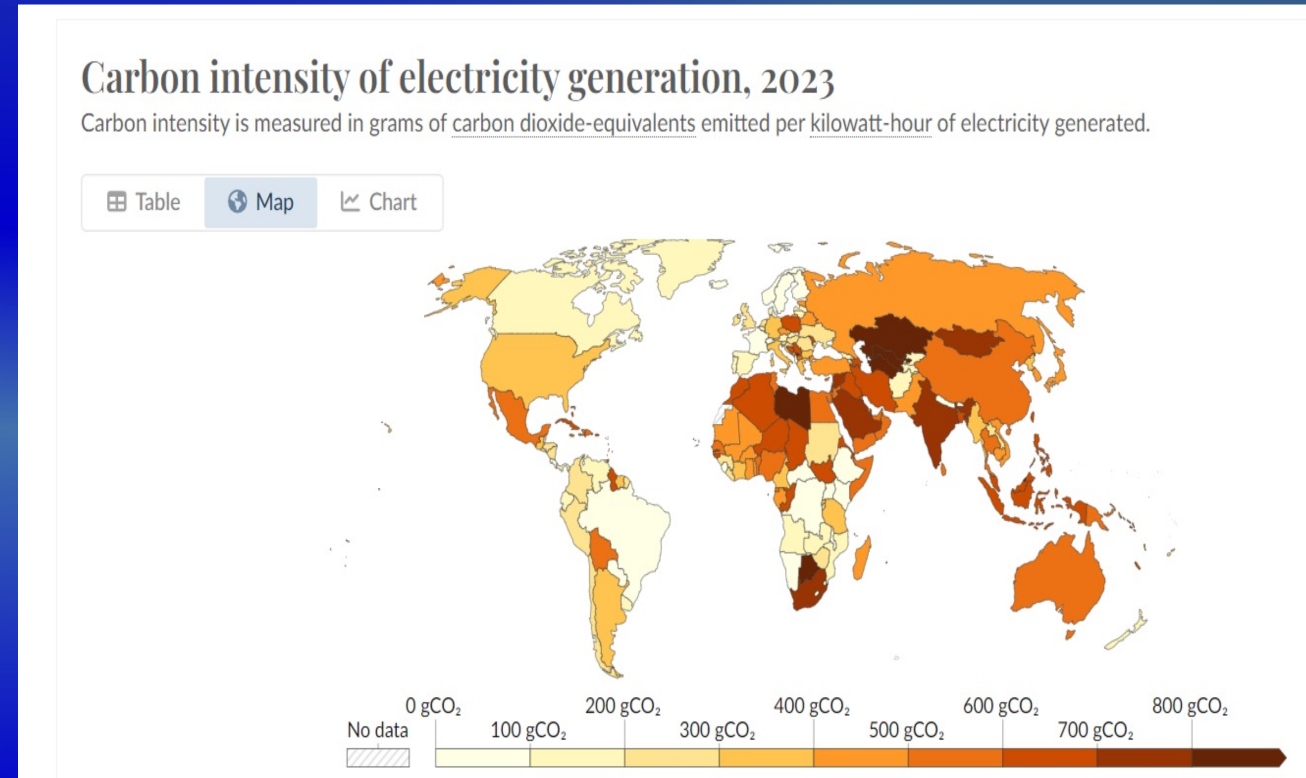
Approaches to Increase Sustainability

- Overall system design
  - Compact accelerator -> high gradients, high field magnets
  - Energy efficient -> low losses
  - Effective -> small beam sizes to maximize luminosities
  - Energy recovery concepts
  - Civil engineering including landscaping and "community" integration
- Subsystem and component design
  - High-efficiency cavities and klystrons
  - Permanent magnets, HTS magnets
  - Heat-recovery. e.g. in tunnel linings, possibly other components
  - Responsible sourcing and material choices for all parts
- Sustainable operation concepts
  - Renewables
  - Adapt to power availability
  - Exploit energy buffering potential
  - Recover energy

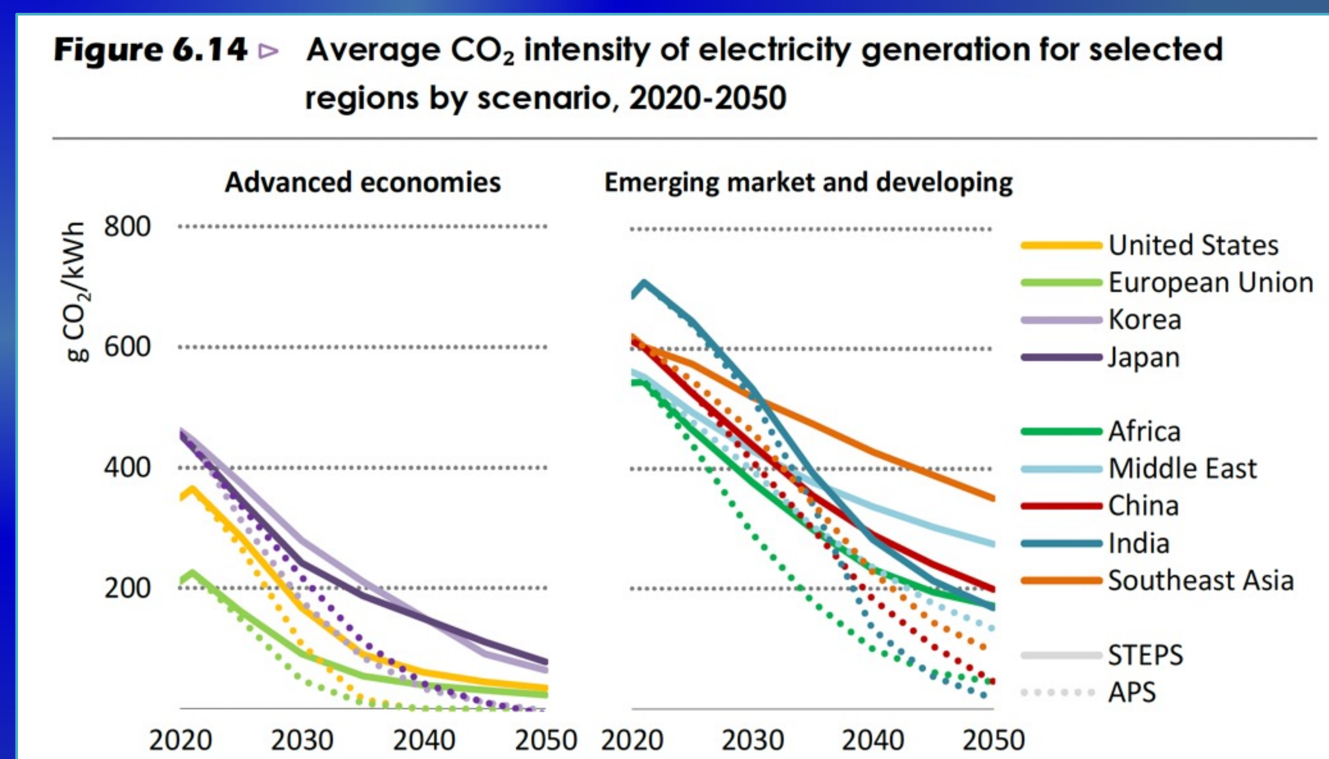
Open Questions: Regional versus Globally Averaged Impacts

- Carbon intensity of electricity production varies enormously across regions &countries
  <u>→ reference values for assumed CO2 intensity of electricity for relevant regions/labs</u>

- Carbon intensity of materials also varies
  - Different local standards
  - Different geology, primary minerals, concentrations
  - Different carbon intensity for local energy, esp. electricity (-> copper, niobium)
- Civil construction: steel and cement mostly from local sources, adhere to local codes
- Result of LCA depends heavily on
  - Source of used materials
  - Construction and operation site
  - LCA Method: use local values or global averages



https://ourworldindata.org/grapher/carbon-intensity-electricity



IEA (2022), World Energy Outlook 2022, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2022, License: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A)

B. List

*Should one evaluate impacts using **site-specific or globally averaged impact** values?*
<u>→ or use general LCA database and move to more local information as the project matures (for materials CO2 content) ?</u>

B. List,
H. Wakeling

Life-Cycle Assessment: Targets and Issues

optimize facility (internal); recommend improvements (Lab/FA); communicate to public (society)

LCA standards for the **assessment of future accelerator** infrastructures **are not set:**

- Common approach how to report and evaluate the data for accelerator RI's (which impact categories, treatment of CO2 intensities, attribution of impacts to long term projects);
- Common table for sustainability parameters, esp. GWP;
- ISO standards may be too rigid for accelerators to perform full LCA → "simplified LCA";
- Many LCA software available → different packages can give different results (data handling)
- LCA database is the most impactful element (global vs. local, age of database, accelerators use non-standard materials, often not available);
- Are there relevant differences in Standards / Methods (e.g. Midpoint ReCiPe 2016 (ILC) vs Endpoint EN 17472 (FCC)) that need to be addressed?

Ultimate Goal:
Collect and provide data in tabular form, provided and endorsed by the projects, for a figure as shown below

(E.g. metric to compare the carbon costs of Higgs factories, balancing physics reach, energy needs, and carbon footprint for both construction and operation)

E. Nanni, M. Breidenbach et al., PRX Energy 2, 047001

PRX ENERGY 2, 047001 (2023)

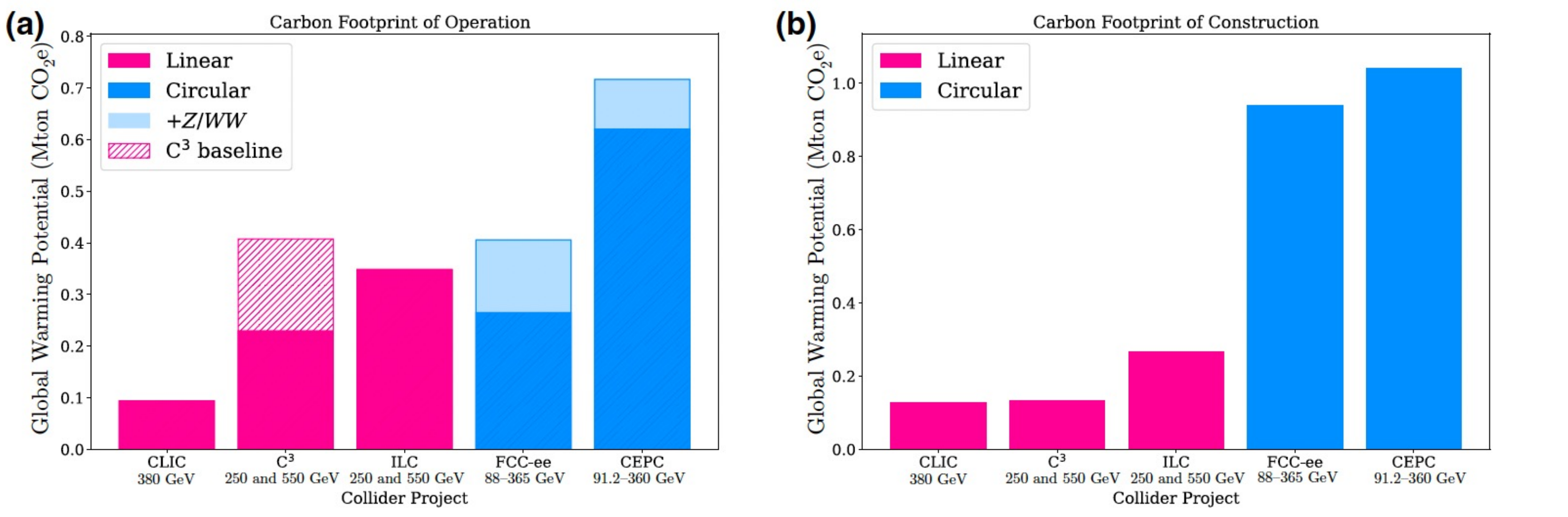
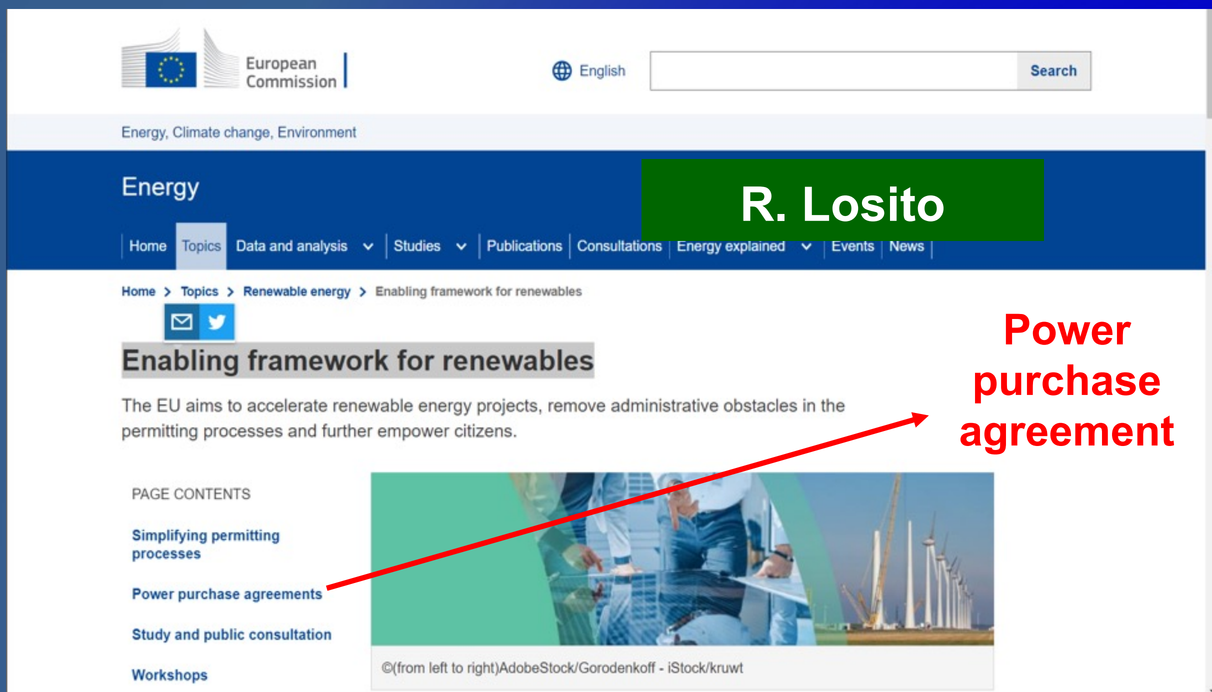


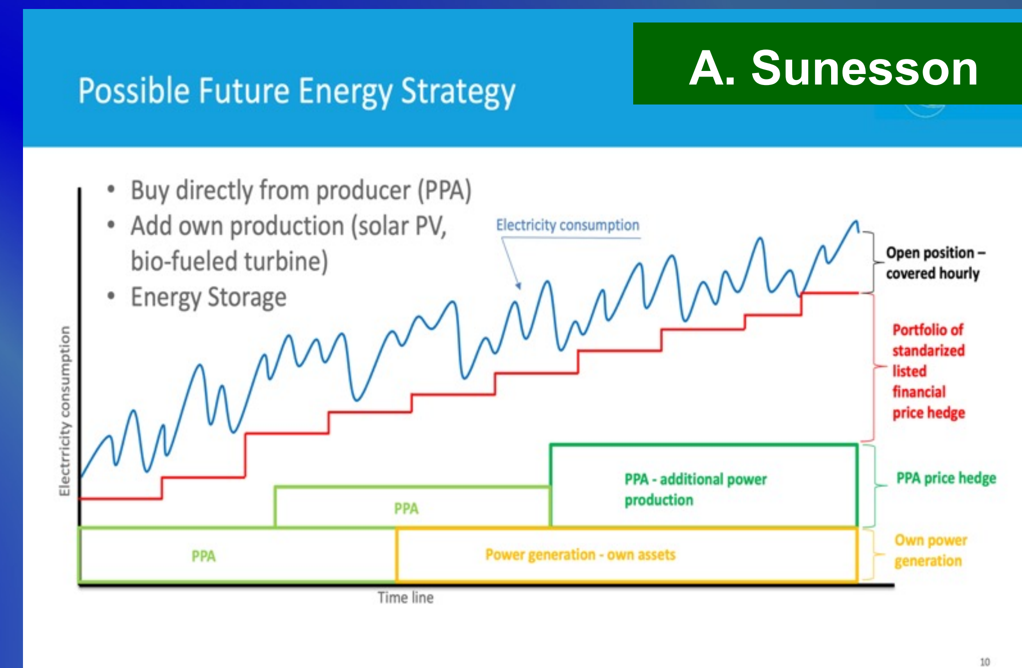
FIG. 5. Global warming potential from (a) operation and (b) construction of all collider concepts. The hashed pink component represents the additional costs of operating C^3 without power optimization, while light blue regions account for additional run modes targeting Z and WW production.

The Future: Fluctuating Energy Sources, Power Purchase Agreements, Running on Renewables

Switch to carbon-neutral energy sources &enabling framework for renewables:

- *power purchase agreement (PPA)* - *long-term contract* for the electricity supply (~ 20 years)



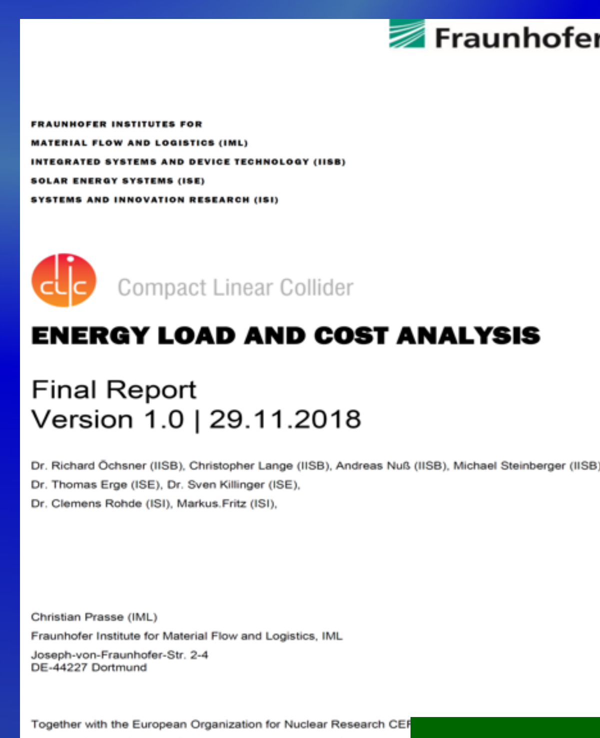


Linear Colliders

- **full collider operation at times of high grid production**
- **reduced operation or standby modes with fast L recovery otherwise**

Study by Fraunhofer institute (2018) considered running CLIC (380 GeV) for a total power of 200 MW (in reality only 110 MW needed) on renewables and participating in ***demand side flexibility:***

- *CLIC's total energy consumption could be generated from renewables (using local solar plant of 330 MWp a local wind farm of 220 MWp)*, but still needs public grid for continuity
- Operating modes with power modulation were investigated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SOLAR ENERGY SYSTEMS (ISE)
SYSTEMS AND INNOVATION RESEARCH (ISI)

Compact Linear Collider

ENERGY LOAD AND COST ANALYSIS

Final Report
Version 1.0 | 29.11.2018

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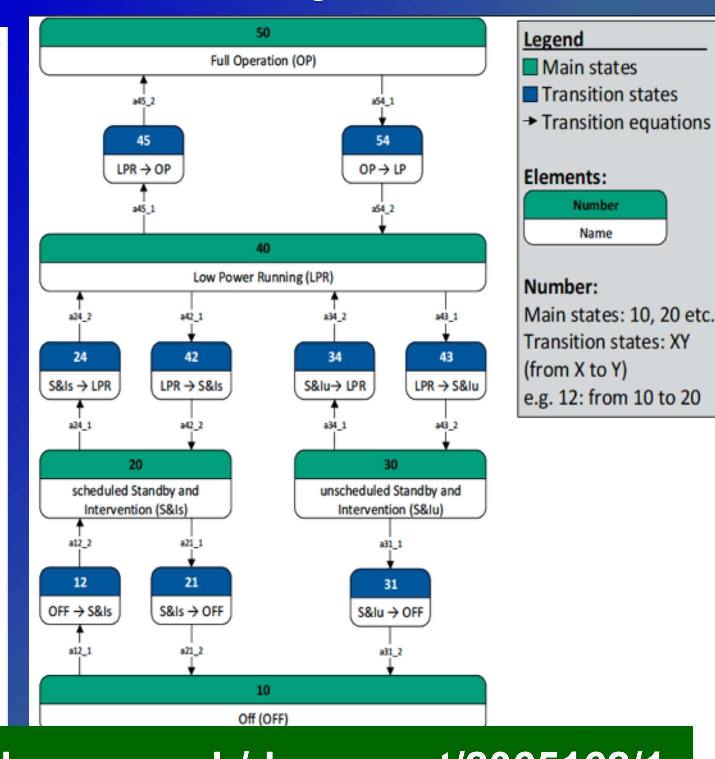
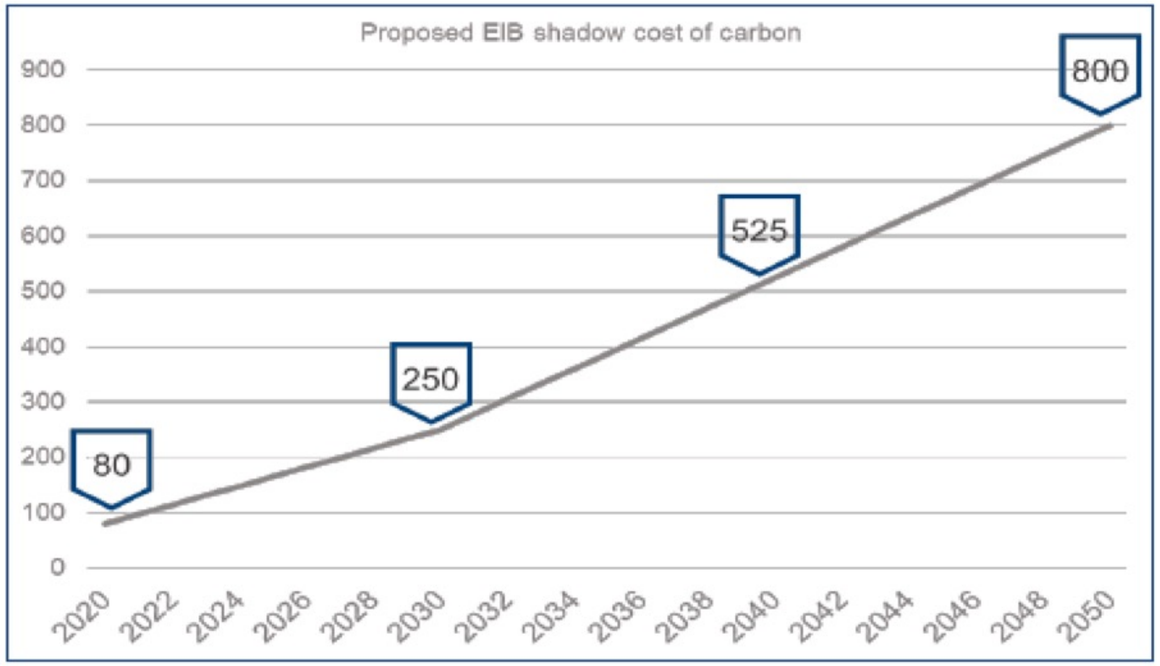


https://edms.cern.ch/document/2065162/1

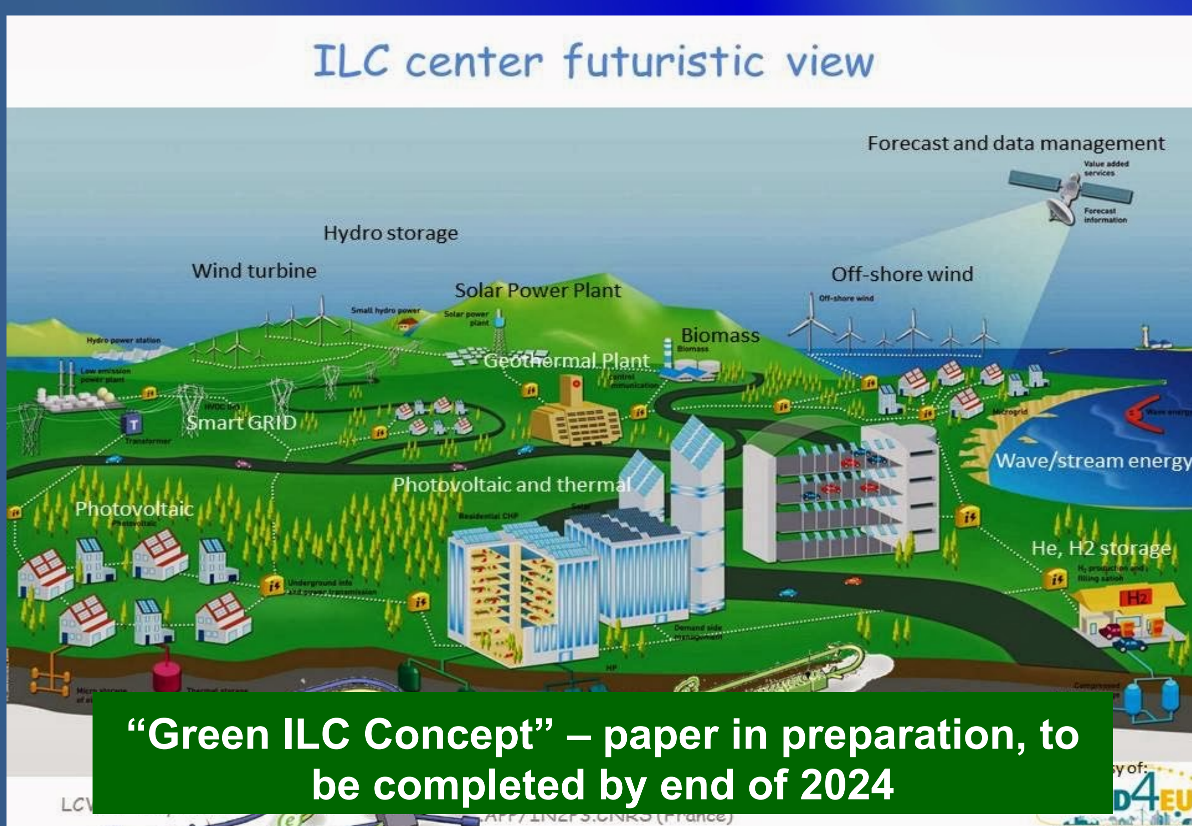
Decarbonisation: Prioritising Nature-Based Interventions

Construction of accelerator large-scale RI's has to face decarbonisation path, with the associated increase of the shadow Carbon cost over the years



https://www.eib.org/attachments/thematic/eib_group_climate_bank_roadmap_en.pdf

- Identifying relevant initiatives to complement decarbonisation efforts:
  - *prioritising nature-based interventions within and around RI's,* integration in local environment as part of the asset management (e.g. CERN generally, Green ILC concept)
  - potential to contribute towards carbon removal through environmental enhancement



"Green ILC Concept" – paper in preparation, to be completed by end of 2024

Figure 7: A single 25 MWh energy storage unit (white containers) built from used electric car batteries, deployed for a PV energy plant in Lancaster, CA (south of Los Angeles, US) put in operate by B2U Storage Solutions in early 2023. Capacities of new systems are increasing fast. A 260 MWh[25] is by now being commissioned and today's largest systems in the range of 1 400 MWh are being extended to 3 000 MWh[26].

J. Gutleber, FCC Renewable Energy Supply Feasibility Study, https://zenodo.org/records/10023947